Determination of the $^{12}N \rightarrow {}^{11}C$+p asymptotic normalization coefficient from the indirect $^{11}C(d,n)^{12}N$ transfer reaction

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The $^{11}C(p,\gamma)^{12}N$ reaction is believed to be an important branch point in supermassive low-metallicity stars because it can produce CNO seed nuclei before the traditional triple-alpha (3α) process turns on. When a star consumes all its pp-chain fuel, and gravitational contraction becomes more dominant than outward thermal expansion, the 3α process turns on too late to prevent the star from collapsing to a black hole. Fuller et.al. [1] showed that the existence of even a small amount of CNO seed nuclei prior to the helium burning stage could slow down the process of collapse and change the destiny of the star. Wiescher et.al. [2] suggested several reaction sequences ("the hot pp-chain"), which lead to the formation of ^{12}C, instead of the traditional 3α process. These include the sequences $^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(e^{+}\nu)^{12}C$ and $^{8}B(\alpha,p)^{11}C(p,\gamma)^{12}N(e^{+}\nu)^{12}C$. Sequences which involve ^{11}C production could be more efficient ways for ^{12}C formation, bypassing the slow 3α reaction, so that the $^{11}C(p,\gamma)^{12}N$ reaction rate and its astrophysical S-factor become of interest.

A GANIL experiment using Coulomb breakup of ^{12}N has shown that direct capture of protons by ^{11}C nuclei is the dominant mechanism and that proton capture through the first two resonance states in ^{12}N becomes less important in the temperature region below $0.3T_9$ [3]. The Asymptotic Normalization Coefficient (ANC) method for determining the direct capture component has been employed using $^{14}N(^{11}C,^{12}N)^{13}C$ at Texas A&M [4], and $^{11}C(d,n)^{12}N$ at Beijing [5]. These two experiments agreed on two conclusions: 1) the astrophysical S-factor and reaction rate based on the extracted ANC values are much higher than were theoretically predicted, and 2) the direct proton capture of ^{11}C leading to the ^{12}N ground state is more important than resonance capture in the temperature region of interest ($<0.3T_9$). However, the extracted ANC values differ from one another by 50%, and the $^{11}C(d,n)^{12}N$ experiment was limited by low statistics, so that its experimental ANC value, $(C_{eff})^2 = 2.86 \pm 0.91$ fm^{-1}, has a large uncertainty [5].

In order to get a more reliable and accurate ANC value, the $^{11}C(d,n)^{12}N$ transfer reaction was repeated with a beam of 150 MeV ^{11}C with 6×10^5 ions/s on a deuterated polyethylene (CD_2) target using BEARS. A 7-strip detector telescope composed of 60 μm ΔE and 1,000 μm E silicon detectors measured emitted ^{12}N particles. For overall system calibration, the $^{12}C(d,n)^{13}N$ reaction was also performed with the same setup and successfully analyzed with DWBA calculations. Excellent agreement was also obtained between the experimental $^{11}C(d,n)^{12}N$ cross sections (θ_{cm}=10.9º to 71.5º) and DWBA calculations. In this experiment, the $^{11}C(p,\gamma)$ ANC value was deduced to be $(C_{eff})^2=1.85 \pm 0.27$ fm^{-1}, which is in good agreement with the published result ($(C_{eff})^2=1.73 \pm 0.25$ fm^{-1}) from the $^{14}N(^{11}C,^{12}N)^{13}C$ experiment. The astrophysical S-factor at zero-energy, S(0) = 0.099 ± 0.020 keV barn, was also calculated based on the extracted ANC value. Figure 1 (a) shows the experimental cross sections compared with theory, and 1 (b) shows the astrophysical S-factor.

In conclusion, a reliable $^{11}C(p,\gamma)^{12}N$ ANC was acquired, and stellar reaction rate from this experiment confirmed that the $^{11}C(p,\gamma)^{12}N$ reaction can occur at lower temperatures and densities than previously believed.

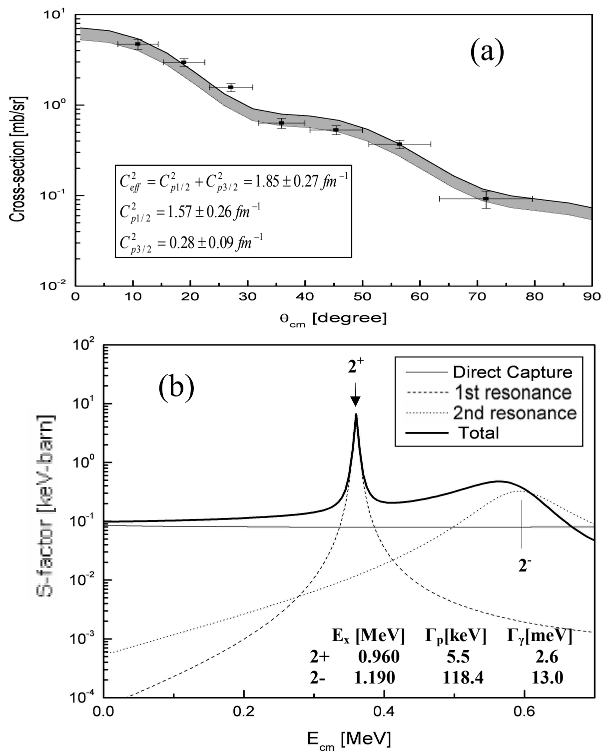

FIG. 1: (a) The $^{11}C(d,n)^{12}N$ experimental cross section compared with the DWBA calculation, and (b) the astrophysical S-factor

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